Simulations using transitional models with in the framework of RANS

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This paper presents the numerical simulation of transitional flows. The present simulation uses transition models in the RANS framework, *viz.* k_T-k_L-ω model of Walters and Cokljat and $\gamma - Re_\theta$ model of Menter *et al.* Both these models are validated for shear flows over flat plate ERCOFTAC test cases. The relative performance of the two transition models for bypass transition flat plate test case (T3A) is discussed. The k_T-k_L-ω model has been successfully used to simulate SD7003 aerofoil $Re = 6 \times 10^4$ and prolate spheroid at $Re = 4 \times 10^4$. and the results obtained are compared with available data.

Keywords: Transition model; Flat plate; SD7003 aerofoil; Prolate spheroid.

1. Introduction

Transition is a complex phenomenon defining the process of the laminar flow changing to turbulent flow. The prediction of transitional flow plays a vital role in the design of various engineering devices including aerospace, turbomachinary etc. Accurate prediction of laminar to turbulent transition is one of the major stumbling block in the development of a general purpose Computational Fluid Dynamics (CFD) tool. In CFD simulation, the transitional flow may be modelled using various methods ranging from the simplest empirical approach to Direct Numerical Simulation (DNS)[1]. It is well known that the Reynolds Averaged Navier Stokes (RANS) based approach is a viable tool for the designer as it compromises between accuracy and expense. Some of the simple approaches to determine flow transition are to use empirical correlations to estimate either the transition onset or the intermittency factor (γ) which are appropriately coupled to the turbulence models. The more recent approach is to use additional transport equations and/or model terms which include the effects of transition on the flow field prediction. In this direction, Walter and Leylek[2] developed a single point model, $k_T - k_L - \omega$ which addresses laminar, transition and fully turbulent flow within the framework of RANS. and successfully applied to resolve transition in complex flows. Furst *et. al.*[3] has successfully used this single point transition model to simulate natural transition, bypass transition and transition due to incoming wake. In order to overcome the need for nonlocal information in the correlation based models, Menter *et. al.*[4] proposed a correlation based transition models using local variables. This transition model which is easily compatible with the modern CFD tools is based on two transport equations, one for intermittency and another for momentum thickness Reynolds number to find the transition onset. Menter and his research group have constantly improved this model and applied to a variety of problems of engineering interest. Paul Malan *et. al.*[5] has provided the missing correlation function in Menter's original paper and successfully used this for a 3D multi-element aerofoil simulation.

This paper presents the work carried out to simulate transitional flow using the $k_T - k_L - \omega$ model and Menter's $\gamma - Re_\theta$ model. The paper discusses the results obtained using $k_T - k_L - \omega$ model to simulate shear flow over flat plate for natural and bypass transition, low Re SD7003 aerofoil and prolate spheroid. The simulation using Menter's $\gamma - Re_\theta$ model is in progress and the results obtained will be discussed in the full paper.

2. Mathematical Formulation

The time-averaged Navier Stokes equations for unsteady incompressible flow in the coordinate-free form is written as follows,

Mass conservation:

$$\bigtriangledown . \rho U = 0 \tag{1}$$

Momentum conservation:

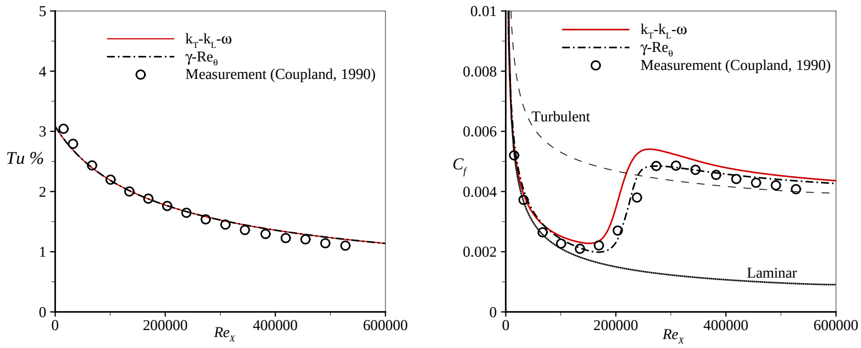
$$D_t \rho U = - \bigtriangledown P + \bigtriangledown .((\mu + \mu_t)(\bigtriangledown U + \bigtriangledown^t U)) \tag{2}$$

Where μ and ρ are fluid viscosity and density, p and U are the time-averaged pressure and velocity vector respectively. The eddy viscosity μ_t is evaluated through turbulence/transition models. The fully turbulent simulation has been carried out using the SST turbulence model[6] where as the transitional flows have been carried out using $k_T - k_L - \omega$ model[2] and Menter's $\gamma - Re_\theta$ model[4,5]. The two transition models have been successfully implemented in the in-house flow code 3D-PURLES (Three Dimensional - Pressure based Unsteady Rans LES solver). The multiblock flow solution code uses a pressure-based implicit finite volume algorithm to solve the unsteady incompressible flow.

3. Results and Discussion

3.1. *Flow over a flat plate*

The two transition models have been successfully used to simulate different ERCOFTAC flat plate test cases[7]. Both the models could predict the variation of turbulent intensity (Fig. 1(a)) as measured in the experiments. The variation of the skin friction coefficient (C_f) as shown in Fig. 1(b) clearly indicate the transition prediction capability of both the models with Menter's $\gamma - Re_\theta$ model having a closer agreement.

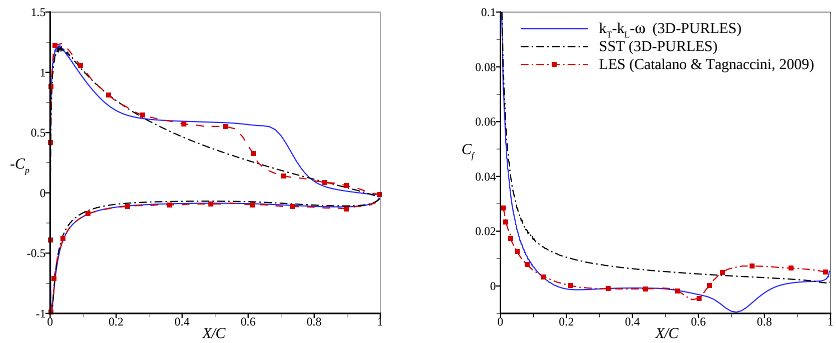


(a) Turbulent intensity (b) Skin friction coefficient

Fig. 1. Flat plate T3A test case ($Re = 6.12 \times 10^5$, $Tu = 3.3\%$, $\mu_t/\mu = 13.3$)

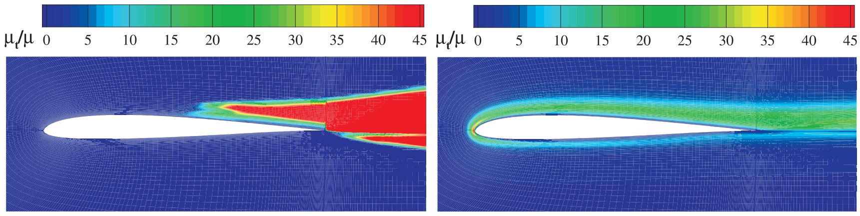
3.2. *Flow past SD7003 aerofoil section*

The results obtained using $k_T - k_L - \omega$ model for the low Re SD7003 aerofoil at few typical angles of attack are compared with LES results[8]. Fig. 2 shows that unlike SST model, $k_T - k_L - \omega$ model could capture the flow transition phenomenon similar to LES data. However it is observed that the onset of transition predicted by the present simulation is delayed when compared to the LES results. The computed particles traces (not shown here) indicated that only $k_T - k_L - \omega$ model could capture the laminar separation bubble. Fig. 3, shows the computed eddy viscosity (μ_t) contours. $k_T - k_L - \omega$ model (Fig. 3(a)) could capture the the phenomenon of transition which is indicated by zero μ_t up to $X/C = 0.65$ as reflected in the surface pressure and skin friction distribution (Fig. 2). The μ_t contours for the SST model (Fig. 3(b)) as expected show the flow to be fully turbulent.



(a) Surface pressure coefficient (b) Surface skin friction coefficient

Fig. 2. Flow past SD7003 aerofoil ($Re = 6 \times 10^4$, $\alpha = 4°$, $Tu = 1\%$, $\mu_t/\mu = 1$)

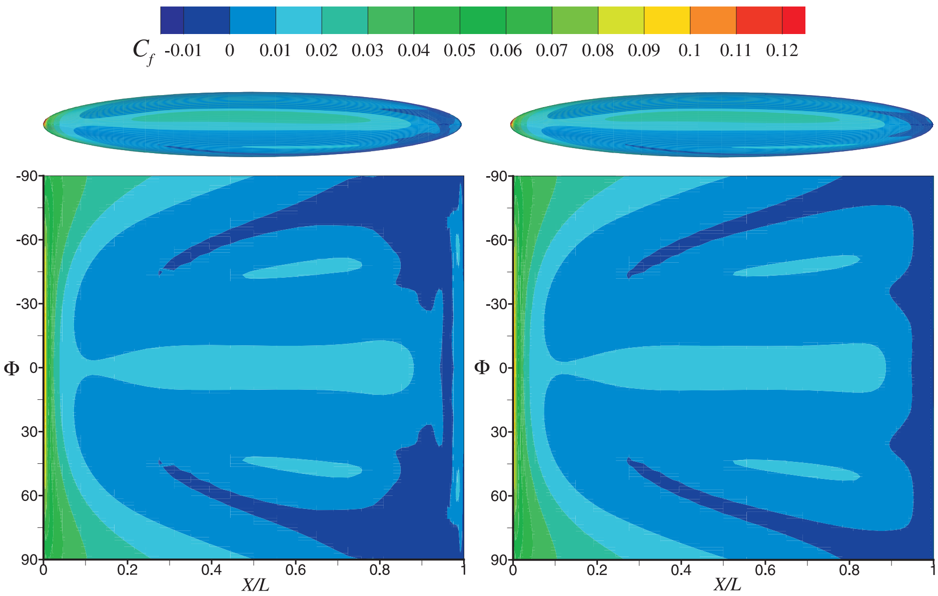


(a) $k_T - k_L - \omega$ transition model (b) SST turbulence model

Fig. 3. Eddy viscosity (μ_t) contours for SD7003 aerofoil ($Re = 6 \times 10^4$, $\alpha = 4°$)

3.3. *Flow past prolate spheroid*

Preliminary analysis have been carried out using $k_T - k_L - \omega$ transition model to simulate flow past prolate spheroid at $\alpha = 20°$ for $Re = 4 \times 10^4$ based on the freestream velocity and model length The surface skin friction contours obtained from the present simulation is shown in Fig. 4. The figure clearly indicates that the variation of skin friction contours obtained using $k_T - k_L - \omega$ model differs from the SST model beyond $X/L = 0.8$. The jump in the C_f contours observed beyond $X/L = 0.8$ for $k_T - k_L - \omega$ model (Fig. 4 (a)) may be attributed to the phenomenon of transition. In order to have a better insight of the capability of $k_T - k_L - \omega$ transition model, work is in progress to simulate at lower angles of attack. The details of the results obtained will be presented and discussed in the full paper.



(a) $k_T - k_L - \omega$ transition model (b) SST turbulence model

Fig. 4. Skin friction contours for prolate spheroid (Re=4×10^4, $\alpha = 20°$, $Tu = 1\%$, $\mu_t/\mu = 1$)

4. Concluding Remarks

The two transition models in the RANS framework have been successfully implemented in the in-house flow solution code. The performance of the two transition models $k_T - k_L - \omega$ and $\gamma - Re_\theta$ have been evaluated for flat plate test cases and both the models perform reasonably well. The skin friction distribution obtained by the $\gamma - Re_\theta$ model for the bypass transition T3A case is observed to have better agreement with the ERCOFTAC data. The results obtained by $k_T - k_L - \omega$ model for the low Re SD7003 aerofoil is in good agreement with the LES data. However the $k_T - k_L - \omega$ model predicts a delayed transition onset as compared to LES data. Preliminary comparison of the results obtained using $k_T - k_L - \omega$ transition model and SST turbulence model for flow past prolate spheroid at $\alpha = 20°$ for $Re = 4 \times 10^4$ indicate that the transition model has some capability to capture the phenomenon of transition.

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